

# **Impacts of ENSO on the South American Summer Monsoon during 1997-99**

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## ABSTRACT

Using the National Center for Environmental Prediction (NCEP) Reanalysis, and CPC Merged Analysis Product (CMAP) rainfall, we have compared and contrasted the anomalies of the South American Summer Monsoon (SASM) during two extreme years of 1997/98 (El Niño) and 1998/99 (La Niña). The results are assessed against a “canonical” ENSO response (CER) pattern for the SASM obtained from empirical mode decomposition based on a previous period (1980-1995). Overall, the SASM anomalies compare well with CER, but with some important differences. Anomalies occurring in the warm phase of the 1997-98 El Niño are very significant and robust, while those occurring in 1998/99 La Niña, appear to be reversed from 1997/98, but are relatively weak and less well-defined. The most pronounced signal in DJF 1997/98 is the development of drought conditions in northern Brazil, excessive rainfall over northern Peru and Ecuador, and over Uruguay and southern Brazil. The tropical rainfall anomalies are associated with the eastward shift of the Walker circulation, which is represented by pronounced low-level anomalous westerlies over the equatorial eastern Pacific and easterlies over northern Brazil. The easterlies are deflected sharply southeastward by the steep topography of the Andes, enhancing the low-level jet (LLJ) along the eastern foothills of the Andes near 15-20°S. The LLJ penetrates deep into the extratropics, yielding rainfall anomalies further poleward compared to CER.

During DJF 1997/98, the eastward expansion of the warm tropospheric temperature over the Niño-3 region causes anomalous geopotential height to develop in the upper troposphere above the Altiplano, leading to a strengthened Bolivian High. An upper-tropospheric jet anomaly maximum is found over the subtropical continent near 30°S, due to increasing meridional gradient of tropospheric temperature, as well as teleconnection patterns linking the

South Pacific and the South Atlantic. Consistent with the CER, the South Pacific High is weakened, and the South Atlantic High is strengthened in DJF 1997/98. However, rather than appearing as a coherent large scale signal over the entire Atlantic as in CER, the South Atlantic High anomalies in DJF 1997/98 split into two separate high pressure centers; one located south of the Amazon basin, and another over the southeastern South Atlantic. The former is induced as a Rossby-wave response by ENSO-induced sinking motion over northern and eastern Brazil, and the latter may be associated with extratropical teleconnection signals. Anomalous convection observed over equatorial western Africa may also have contributed to the different circulation response over the Atlantic in DJF 1997/99 compared to the CER.

Comparison of the evolution of the SASM anomalies in 1997-99 with their corresponding annual cycles, suggest that the anomalies are phase-locked to and represent either enhancement or reduction of the annual variations. Results suggest that, from a system perspective the SASM was strengthened during the 1997/98 El Niño and weakened, albeit to a lesser extent, during the 1998/99 La Niña.

## 1. Introduction

The occurrences of severe droughts, known as Nordeste droughts, at intervals of 2-7 years with devastating impacts in the Amazon and Northeast Brazil have been known for a long time (Walker 1928). Recent studies (Hastenrath 1978, Ropelewski and Halpert 1987, Rasmusson and Mo 1993, Nogués-Paegle *et al.*, 2001 and many others) have shown that the Nordeste droughts are caused by the eastward shift of the Walker circulation associated with the warming of the central-eastern Pacific and the anomalous local Hadley circulation induced by the anomalous strong inter-hemispheric gradient of the tropical Atlantic sea surface temperature (SST) during El Niño Southern Oscillation (ENSO). Results from dynamical models suggested that the reduced latent heating from deficient rainfall over the Amazon Basin during El Niño, may reduce the intensity of the Bolivian High in austral summer, and hence may lead to a weakening of the South American summer monsoon (SASM) during an El Niño (Silva Dias *et al.* 1983, Bell *et al.* 1999 and others).

On the other hand, Douglas *et al.* (1999) showed that the low-level jet (LLJ) at Santa Cruz, Bolivia was strengthened during a special pilot balloon observation period in the austral summer of 1997/98. Zhou and Lau (1997) found a statistically significant positive correlation between the tropical eastern Pacific sea surface temperature (SST) and the strength of low-level jet (LLJ) along the eastern foothills of the tropical-subtropical Andes in austral summer. They also found increased rainfall in subtropical South America, in the region of Uruguay and Southern Brazil, in conjunction with an increase in the LLJ. Since the LLJ and rainfall over subtropical South America are integral parts of SASM (Zhou and Lau 1998), the above results suggested that SASM might be enhanced during an El Niño.

Thus there appear to be two contradicting views regarding the response of the SASM to El Niño. A possible reason for this conundrum is that the SASM is an extremely complex phenomenon, including forced (deterministic) and intrinsic (chaotic) components. Hence, the SASM and its response to ENSO should not be characterized by the behavior of a single observable, but rather should be viewed as a climate subsystem with many interacting components. In this paper, we assess the impacts of the 1997/98 El Niño and 1998/99 La Niña on SASM with an aim to better understand the mechanisms of the responses of SASM to ENSO, from a climate subsystem viewpoint. In Section 3, we first discuss key features of rainfall and circulation climatologies of SASM and define a "canonical" ENSO response (CER) of SASM based on empirical mode decomposition for the period 1980-1995. In Sections 4 we discuss the impacts of 1997-99 ENSO on the SASM regional rainfall, temperature and circulation anomalies and their dynamical linkages in relation to the climatology and CER. The evolution of key SASM variables in relation to their corresponding annual variations and the timing of ENSO SST forcing will be discussed in Section 5. The conclusions are presented in Section 6.

## **2. Data**

The key data set used in this study is the monthly mean National Center for Environmental Prediction (NCEP) reanalysis (Kalnay *et al.* 1996). The spatial resolution of the data is  $2.5^\circ$  latitude  $\times$   $2.5^\circ$  longitude with 17 pressure levels in the vertical. Despite the coarse resolution and the lack of observations over South America, the NCEP reanalysis data have proven to be useful in providing a basic description of the mean and variability of the regional climate of South America (Kousky and Ropelewski 1997, Hastenrath 2000). For SST, we use the monthly NCEP  $1^\circ \times 1^\circ$  analysis based on optimum interpolation. The SST analysis incorporates *in situ* data from the Global Telecommunication System, and satellite observations

from the National Environment Satellite, Data and Information Service (NESDIS) since 1990 (Reynolds and Smith 1994). For rainfall, we use the Climate Analysis Center Merged Analysis Product (CMAP) data, which merge satellite-derived rainfall estimates over oceans and gauge observations over land on a  $2.5^{\circ} \times 2.5^{\circ}$  latitude-longitude global grid (Xie and Arkin 1997).

### **3. Climatology and interannual variability**

#### *a. Climatology*

Climatologically, the austral summer of South America possesses two rainfall regimes: an oceanic rainfall regime associated with the Intertropical Convergence Zone (ITCZ) over the equatorial Atlantic and northern Brazil, and a continental rainfall regime of the SASM encompassing the land region between  $10^{\circ}\text{S}$  to  $25^{\circ}\text{S}$ , including Bolivia, central and southern Brazil, Paraguay, Uruguay and northern Argentina (Fig.1a). In middle to late November, the convection over northwestern South America weakens, and the leading edge of continental precipitation regime abruptly advances southward more than 10 degrees from northwestern Brazil to the La Plata Basin of Paraguay and northern Argentina, signaling the onset of SASM. During December-January- February (DJF), monsoon rain prevails over most subtropical land area of the La Plata Basin. The maximum rainfall axis tilts northwest-southeastward, extending into and merging with the South Atlantic convergence zone (SACZ), which is most active in DJF. The SASM continental rainfall regime between latitudes  $10^{\circ}\text{S}$ – $25^{\circ}\text{S}$  can be characterized by a seasonal concentration of 40% or more of the annual rainfall occurring in DJF. This rainfall regime is distinct from that over northern Northeast Brazil and the equatorial Atlantic ITCZ, which begins to develop in March, and peaks in April – May (Zhou and Lau 2000, Hastenarath 2000).

As the land-ocean heating contrast increases approaching austral summer, surface pressure rises over northern Africa and lowers over subtropical South America. The pressure gradient drives a low level perturbation wind system which emanates from the high pressure center of northwestern region of the African continent, blows eastward across the northern equatorial Atlantic Ocean, crosses the equator and turns poleward, and terminates in the Gran Chaco low over southern Brazil (see Fig. 1b). In the subtropics, the seasonal low-level flow is channeled by the steep topography of the Andes yielding an elongated LLJ along the eastern foothills of the tropical Andes between 10°S to 20°S. The LLJ brings copious moisture and rain to the La Plata Basin of subtropical South America. Additionally, the SASM climate is strongly regulated by the subtropical highs, *i.e.*, the South Atlantic High (SAH) and the South Pacific High (SPH) on opposite sides of the continent. The anticyclonic flow around the SAH brings moisture from the South Atlantic to southeastern Brazil and northern Argentina. It interacts with the subtropical westerlies, in determining the strength and the location of the South Atlantic Convergence Zone (SACZ). On the other hand, the SPH provides the upstream linkage to ENSO related anomalies in the South Pacific and regulates the extratropical influence of the SASM.

*b. The Canonical ENSO Response (CER)*

The impacts of ENSO on the South American summer rainfall have been documented by many previous studies (Walker 1928, Hastenrath 1978, Ropelewski and Halpert 1987, and others). The following provide a basic description of ENSO impacts on the SASM, based on empirical orthogonal function analysis of DJF rainfall and wind data for the period 1980-1995 (Zhou and Lau 2000). The features described in the following will be used as a benchmark to evaluate the 1997/98 and the 1998/99 events. It should be pointed out that the CER depicts common features shared for ENSOs occurred during the aforementioned period. Individual

cases may differ substantially from CER. Whether the 1997-99 events are fundamentally different from previous events cannot be determined by the present analysis.

The CER features deficient rainfall in Northeast Brazil and central Amazon, excessive rainfall over the west coast of Ecuador and northern Peru, and the La Plata Basin, Uruguay and southern Brazil (Fig. 2a). The northwest African High and the SAH are enhanced, while the subtropical highs of the South Pacific and the western North Atlantic are weakened (Fig.2b). This large-scale surface pressure anomaly pattern is consistent with the eastward shift of the Walker Circulation during an El Niño, evidenced by low level westerly anomalies over the equatorial eastern Pacific and anomalous easterlies over the equatorial Atlantic. The convergence pattern of the anomalous wind is dynamically consistent with the excessive rainfall (rising motion) over Ecuador and northern Peru, and the deficit rainfall (subsidence) over northern Brazil. The extended fetch of easterlies over the equatorial Atlantic and the large-scale double anticyclones covering the northern and southern Atlantic suggest that the induced subsidence is very large scale. The anomalous easterlies over northern Brazil turn sharply southeastward as they are deflected by the Andes, leading to an enhanced LLJ. The increased SAH yields pronounced anticyclonic (geostrophic) flow around the entire South Atlantic, yielding strong northeasterlies over eastern subtropical South America, and enhancing the climatological flow and rainfall over the region.

#### **4. SASM anomalies in 1997/98 and 1998/99**

The years 1997-1999 witnessed the strongest ENSO event of the 20<sup>th</sup> century. Features of global rainfall anomaly patterns have been reported by a number of studies (see Bell *et al.* 1999 for an overview). The following analysis will focus on the SASM system and the comparison with the climatology and the CER described in Section 3. In addition, we will explore new

features that will shed light on the question of whether the SASM was enhanced or reduced during the 1997/98 and the 1998/99 events.

*a. Rainfall and circulation anomalies*

The rainfall anomaly pattern during DJF of 1997/98 is basically similar to the CER, showing excessive rainfall over the equatorial eastern Pacific, southern Brazil-Uruguay-Northern Argentina region, and deficient rainfall over Central America, northern Brazil and the equatorial Atlantic (see Fig. 3a). The rainfall deficit over the interior of the continent including central Amazon appears to be more extensive compared to the CER shown in Fig. 2a. Also noticeable is enhanced rainfall along the west coast of equatorial central Africa (0-15°S), which be an extension of the rainfall excess found over eastern Africa during El Niño (not shown in Fig. 3a).

The large scale circulation anomalies during DJF 1997/98 shows the eastward shift of the Walker circulation as evident in the pronounced anomalous 850-hPa westerlies over the tropical eastern Pacific and easterlies over northern Brazil (Fig. 3b). However, anomalous westerlies are observed over the equatorial Atlantic, instead of anomalous easterlies in the ENSO norm (Fig. 2b). The anomalous westerlies extend eastward to the west coast of central Africa, and beyond. These features suggest an anomalous Walker circulation in DJF 1997/98 that is more compact in horizontal scale compared to CER, with strong subsidence concentrated over northern Brazil, and additional rising motion over the west coast of central Africa. The enhanced subsidence over northern Brazil is evident in the presence of two robust low level anticyclones on opposite side of the equator respectively, with the equatorial easterlies sandwiched between them. The above circulation pattern can be identified with the Rossby wave response to a near equatorial heat sink over northern Brazil (Gill 1980). Similar to the CER, the low level anomalous easterlies are deflected southeastward by the Andes, resulting in an enhancement of the

climatological LLJ. The enhanced LLJ acts as a “conveyor belt” bringing more moisture from the Amazon region to subtropical South America. Compared to the CER, the LLJ in 1997/98 penetrates deeper into the extratropics resulting in maximum rainfall anomaly about 5 latitude further polewards. As in the CER, the South Pacific High is weakened in 1997/98, as evident in the anomalous low found off the coast of Chile. Also found is a secondary anomalous anticyclone over the southeastern South Atlantic and a pair of cyclones over the equatorial western Africa. The cyclone-anticyclone system may be a part of a global teleconnection in the southern hemisphere (see discussion in Section 4c). Overall, there is a lack of large-scale response of the SAH over the entire Atlantic in 1997/98 compared to the CER. In 1997/98, the strong low-level anticyclone over southern Brazil yields anomalous southerlies off the coast of subtropical eastern South America, opposing the climatological flow there (see Fig.1b). The circulation pattern in Fig. 3b suggests that the excessive rainfall in Uruguay/Southern Brazil is principally due to the enhancement of the LLJ, forced by the anticyclonic flow induced by reduced heating in northern Brazil.

The rainfall and circulation anomalies in DJF 1998/99 are less defined compared to those of 1997/98. Excessive rainfall is found over northwestern South America, and deficient rainfall over northeastern and eastern Brazil (Fig.4a). Over subtropical southeastern South America, the rainfall anomaly pattern suggests a southward shift of the SACZ. The anomalous Walker circulation appears to have reversed from that in DJF 1997/98, as evident from the presence of low-level anomalous westerlies over equatorial northwestern South America, coupled to a pair of cyclones with centers over Columbia and Bolivia/western Brazil respectively (Fig. 4b). These features are consistent with increased tropical heating from increased rainfall over northwestern South America. The anomalous LLJ has completely reversed from a year ago, featuring a

northward “conveyor belt” emanating from a cyclonic center off the coast of Uruguay ( $\sim 35^\circ$  S), and merging with the cyclonic circulation over Bolivia and western Brazil. This circulation pattern suggests a weakening of the climatological SASM low-level circulation. Circulation features over the southeastern Atlantic and eastern Africa remain similar to those found in DJF 1997/98, suggesting the presence of lower frequency forcing in that region.

*b. Geopotential anomalies*

In this subsection, we discuss the anomalies in the upper troposphere height field with respect to the observed rainfall and low-level circulation anomalies. In the austral summer climatology (Fig.5a), the most outstanding regional features are the Bolivia High ( $15\text{--}20^\circ$ S,  $70^\circ$ W) and a low pressure center over the western tropical South Atlantic. The former has been attributed to the Amazonian heating and the effect of elevated heat source by the Altiplano (Silva Dias et al. 1983, Rao and Erdogan 1989, Lenters and Cook 1997, Zhou and Lau 1998, Chen *et al.* 2000). During DJF 1997/98, increased height anomalies are found over the entire tropics (Fig.5b). Over the eastern tropical Pacific, the anomalous high-pressure ridges on both sides of the equator are indicative of an anomalous heat source (rising motion) over the equatorial eastern Pacific. The low superimposed on the tropical South Atlantic trough signals the presence of a heat sink (subsidence). The southern ridge extends southeastward, over the Altiplano, across the southeastern Brazil, reaching the southeastern South Atlantic. Hence the Bolivia High is increased as a direct hydrostatic response to El Niño, which opposes the effect due to reduced heating over northern and central Brazil. The high over the southeastern South Atlantic approximately collocates with the lower tropospheric anticyclone (see Fig.3b), suggesting an equivalent barotropic vertical structure, typical of extratropical teleconnection patterns. Another pronounced feature is an elongated low height anomaly in the southwestern region of the

domain, which contrasts with the generally increased height in the tropics. The tight latitudinal gradient suggests a very strong westerly geostrophic jet stream near 25-35°S spanning the southeastern Pacific, subtropical South America and the southeastern Atlantic. The height pattern suggests the possibility of an extratropical wavetrain (Kang *et al.* 2001) connecting SASM anomalies to the South Pacific and southeastern Atlantic.

In DJF 1998/99, the 200-hPa height features reduced height over the tropical eastern Pacific and western-central tropical South America, consistent with the tropospheric cooling associated with La Niña (see Fig.5c). Over the tropical Atlantic, two anomalous upper highs replace the lows in 1997/98. The most notable feature is the stationary wave pattern in the extreme southern part of the domain, anchored by two high-pressure centers over the southeastern South Pacific and South Atlantic respectively. Embedded in between the two highs is a strong low near 30-35°S, 55°W over Uruguay with center slightly shifted westward with respect to the center of the surface anticyclone, suggesting baroclinic effects. This feature may be related to the poleward shift of the SACZ noted previously.

### *c. Vertical structures*

To illustrate the vertical extent of the SASM anomalies, vertical cross-sections of the climatological and anomalous temperature and circulation are examined.

#### (i) TROPOSPHERIC TEMPERATURE

The thermal contrast between the South America land mass and the adjacent oceans on both sides of the continent is obvious in the climatology with the zonal mean removed as shown in Fig. 6a. The increased temperature due to heating over the Altiplano can be detected up to 200 mb. During DJF 1997/98 the induced tropospheric warming has a large vertical scale,

starting from  $1^{\circ}\text{K}$  at the surface in the Niño-3 region ( $120^{\circ}\text{W} - 140^{\circ}\text{W}$ ) and increasing upward to a maximum of  $3^{\circ}\text{K}$  between 500 and 200 hPa (Fig.6b). In the upper troposphere the warming area expands eastward, across South America to the Atlantic, with a magnitude of  $1 - 1.5^{\circ}\text{K}$  over the region of the Altiplano ( $\sim 65^{\circ}\text{W}$ ). The rapid expansion of the temperature anomaly in the upper troposphere has been attributed to temperature advection effects (Lau *et al.* 1998) and appears to contribute to the enhancement of the Bolivia High in DJF 1997/98. Interestingly, over the oceanic region of  $80^{\circ}\text{W} - 100^{\circ}\text{W}$ , off the coast of Peru, a shallower vertical structure is found below 500 -600 hPa. This shallow structure may be related to the regional monsoon modes reported by Trenberth *et al.* (2000). Physically, it may be linked to diabatic heating associated with changes in stratus clouds in that region during an El Niño. In DJF 1998/99, the tropospheric temperature is less extensive with negative anomaly pattern directly overhead the Niño-3 region (Fig.6c). The shallow temperature anomaly near  $80 - 100^{\circ}\text{W}$  appears to have intensified, with the sign reversed near the surface. Elsewhere the anomalies are weak compared to those in DJF 1997/98.

## (ii) ZONAL WINDS

Because of the extensive tropospheric warming in the tropics during 1997/98, the temperature gradient between the tropics and extratropics increases. Through the thermal wind, the increase gradient will impact on the subtropical westerlies in the upper troposphere. Figure 7 shows the vertical cross-sections of the climatological and anomalous zonal winds along a north-south strip between  $50 - 80^{\circ}\text{W}$ . In the climatology, a westerly maximum is found in midlatitudes around  $40 - 45^{\circ}\text{S}$ , with a maximum of  $26 - 28 \text{ ms}^{-1}$ . In DJF 1997/98, the jet stream shifts equatorward, as indicated by an anomalous jet stream maximum of over  $8 \text{ ms}^{-1}$  at 100-200 hPa at  $30^{\circ}\text{S}$ , coinciding approximately with the latitude of maximum precipitation in subtropical

South America. The zonal wind anomalies are largely geostrophic stemming from thermal wind balance associated with the increasing thermal gradient between the tropics and midlatitudes. North of the jet maximum, the decreasing zonal wind to the north above 500 hPa will contribute positive vorticity anomaly over the Bolivia High (15 – 18°S). As noted in the 200 hPa height anomalies, the zonal wind maximum may also be a part of stationary wave or teleconnection signal in the southern hemisphere stemming directly from ENSO heating over equatorial central Pacific. Thus the zonal wind structure suggests that excessive SASM rainfall anomalies over Uruguay and southern Brazil in DJF 1997/98 may be the result of reinforcement of tropical and midlatitude effects. In DJF 1998/99, the upper level zonal wind structure changes drastically with generally negative anomalous zonal winds in the upper troposphere. Two distinct easterly anomaly maxima are found: one over the tropics near 12-15°S and one over 40°S, indicating the separate effects of tropical cooling due to La Niña and extratropical teleconnection (see Fig 5c).

### (iii) MERIDIONAL WINDS

The vertical cross-sections of the climatological and anomalous meridional wind ( $v$ ) along 15° S from 80° W to 55° W are shown in Fig.8. Climatologically the LLJ (negative- $v$ ) is confined to below 700 hPa, and is coupled to a return flow (positive- $v$ ) in the middle to upper troposphere (Fig.8a). This may be viewed as the local meridional overturning forced by subtropical heating associated with the SASM. Above 500hPa, the southerlies are connected to the northerlies (negative- $v$ ) to the west of the Altiplano (~70°W), as part of the large-scale anticyclonic flow around the Bolivia High. During DJF 1997/98, the LLJ is substantially enhanced, expanding both laterally and vertically, and the return flow is confined to the upper troposphere and shifted toward the Altiplano. As shown previously, the increase in the northerly flow in 1997/98 is largely associated with Rossby wave response induced by reduced diabatic

heating over northern Brazil. The deep vertical structure of the LLJ anomalies is likely due to the channeling effect of the Andes. During DJF 1998/99, the LLJ has reversed sign, with anomalous equatorward flow (positive- $v$ ) confined to below 800mb. The meridional flow is less organized with smaller vertical scales, indicating the lesser impact of the 1998-99 La Niña.

## 5. Seasonality

In this section, we examine the time evolution of key features of SASM anomalies with respect to the corresponding seasonal cycles and to the anomalous SST forcing during the 1997-99 ENSO variation. Figure 9 shows that generally the anomalies are phased-locked to the seasonal cycle. The warming of SST over the Niño-3 region relative to the annual cycle commences around June 1997, peaking in March 1998, and reverses sign after August 1998 (Fig.9a). Notice that the SST anomalies are much smaller in DJF 1998/99 compared to the 1997/98. This may be a reason why the anomalies in the former are generally much smaller and less defined compared to the latter. The climatological low-level easterlies over northern Brazil follow a distinct semi-annual cycle, with the easterlies substantially enhanced during DJF 1997/98 and weakens in DJF 1998/99 (Fig. 9b). Rainfall over Uruguay/Southern Brazil (50-60°W, 20-30°S) rises above normal starting in September 1997 when the El Niño is well developed, and peaks in February, with rainfall amount increased by more than 70% of its climatological mean (Fig. 9c). The LLJ (Fig. 9e) appears to strengthen at the first sign of SST warming in May 1997, reaching a maximum in DJF 1997/98 about the same time as the low level easterlies. Notice that the peak rainfall in the subtropics appears to lag the maximum in the low level easterlies and the LLJ by about one or two months.

The upper troposphere geopotential height anomaly over the Altiplano (Fig 9e) evolves in tandem with the tropospheric mean temperature (not shown), beginning with a 2-3 month

delay with respect to Niño-3 SST warming. However the warming over the Altiplano is accelerated in DJF due to rapid heating over the land associated with the SASM, peaking in February 1998, while the Niño-3 SST continues to rise. The South Pacific High depicts a well define above-normal and below-normal phase leading the Niño-3 SST by about one to two months. During DJF 1997/98 the SAH is slightly strengthened, but near normal in DJF 1998/99, and appears to evolve somewhat independent of the Niño-3 SST. As discussed previously, during 1997-99, the SAH may be affected by anomalous heating over western Africa and teleconnection pattern forced from SST anomalies in the equatorial central Pacific. The upper troposphere subtropical zonal wind (Fig 9h) generally shows positive anomaly (westerlies) during the warm phase of Niño-3 SST, but near normal conditions during the cold phase. The initiation of upper level westerly anomalies from August to September appears to coincide with strengthening of the LLJ, suggesting an enhancement of the local (reversed) Hadley circulation with rising motion over the subtropics. In addition, there appears to be large fluctuations of the subtropical westerlies that are unrelated to the development of ENSO, but more likely related to the internal variability of the southern hemisphere extratropics.

## **6. Conclusions**

In this paper, we have compared and contrasted the anomalies of the SASM system in recent two SST extreme years of 1997/98 (El Niño) and 1998/99 (La Niña,) with respect to the CER. Overall, the 1997-99 SASM anomalies are consistent with the canonical patterns, but important differences are also noted. Similar to the CER, during DJF, 1997/98, two tropospheric anomalous warming anomalies are found straddling the equator over the central-eastern equatorial Pacific. The anomalies stretch northeastward and southeastward to the Gulf of Mexico and South America respectively. The southern branch reaches the Altiplano Plateau and

significantly enhances the Bolivian High. Also found is an equatorward displacement of the upper-tropospheric jet over the subtropical continent, consistent with the increased thermal gradient between the tropics and extratropics. The El Niño-induced anomalous mass distribution is represented by pressure increase over northwestern Africa and the subtropical South Atlantic and decrease from the subtropical South Pacific to Gran Chaco of South America, reinforcing the summertime regional pressure gradient. As a result of the direct response to ENSO SST forcing, an anomalous Walker circulation is developed, with anomalous rising motion and low-level westerlies over the equatorial eastern Pacific and subsidence and anomalous easterlies over northern Brazil. Due to the deflection by the Andes, the low-level easterlies turn sharply southeastward, propelling an intense northwest LLJ along the eastern foothill of the tropical-subtropical Andes. The enhanced LLJ appears to be the main cause of the excessive rainfall found in the Uruguay/Southern Brazil region during DJF 1997/98.

As in CER, the SPH is weakened in 1997/98, reflecting the weakening of the Walker circulation. A major difference between CER and 1997/98 SASM response is in the displacement of the SAH, which appears to split into two low level anticyclones one found immediately to the south of the Amazon Basin, and one over the southeastern Atlantic. The former is directly related to the Rossby wave response to sinking over northern Brazil and the latter may be induced by teleconnection signal linking the South Pacific and the South Atlantic during DJF 1997-98. The low-level meridional wind associated with the anomalous Amazon anticyclone reinforces the LLJ along the Andes, and constitutes the lower branch of an induced local Hadley cell, with rising motion over subtropical South America, upper troposphere equatorward flow, and sinking branch over northern Brazil. Anomalous convection over the west coast of central Africa may have also contributed to anomalous low-level *westerlies* over

the equatorial central Atlantic during 1997/98 (Fig.2b) as opposed to the low-level *easterlies* in CER (Fig.3b). It is possible that the excessive convection over the western Indian Ocean during DJF 1997-98 (Webster et al. 1999) may also be influenced the SAH. A 3-D illustration of the key features of the responses of the SASM/LLJ complex to El Niño is shown in Fig.10.

Analysis of the time evolutions of the SASM anomalies show that they are strongly phased locked to the annual variations, indicating that in addition to the ENSO forcings, the annual cycles play a key role in determining the phases and amplitude of the SASM responses. Overall, our results suggest that the SASM is strengthened during DJF 1997/98 and weakened during DJF 1998/99. One possible reason is that the exceptional strong direct thermal forcing from the 1997-98 El Niño has resulted in an enhanced Bolivian high, which more than compensates the possible reduction due to dynamical impact from reduced heating over the Amazon. This study also brings to light the ENSO influence on South American summertime climate via the large-scale thermal and dynamical responses of the entire SASM system.

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## FIGURE CAPTIONS

Figure 1 a) 1979-1999 DJF rainfall climatology. b) Departure of DJF mean sea level pressure (hPa) and 850-hPa wind (mm/day) from the corresponding annual mean

Figure 2 The canonical ENSO response: a) DJF rainfall EOF pattern. b) Regression of the principal component with SLP and 850-hPa wind (From Zhou and Lau 2000).

Figure 3 a) 1997/98 DJF rainfall anomaly (mm/day), and b) corresponding abnormal 850 hPa wind (m/s) and streamline.

Figure 4 Same as Fig.3 except for 1998/99 DJF.

Figure 5 a) DJF 200 hPa geopotential height of 1979-1999 climatology (-12000 gpm, not contoured when smaller than 300 gpm), b)1997/98 anomaly, and c)1998/99 anomaly.

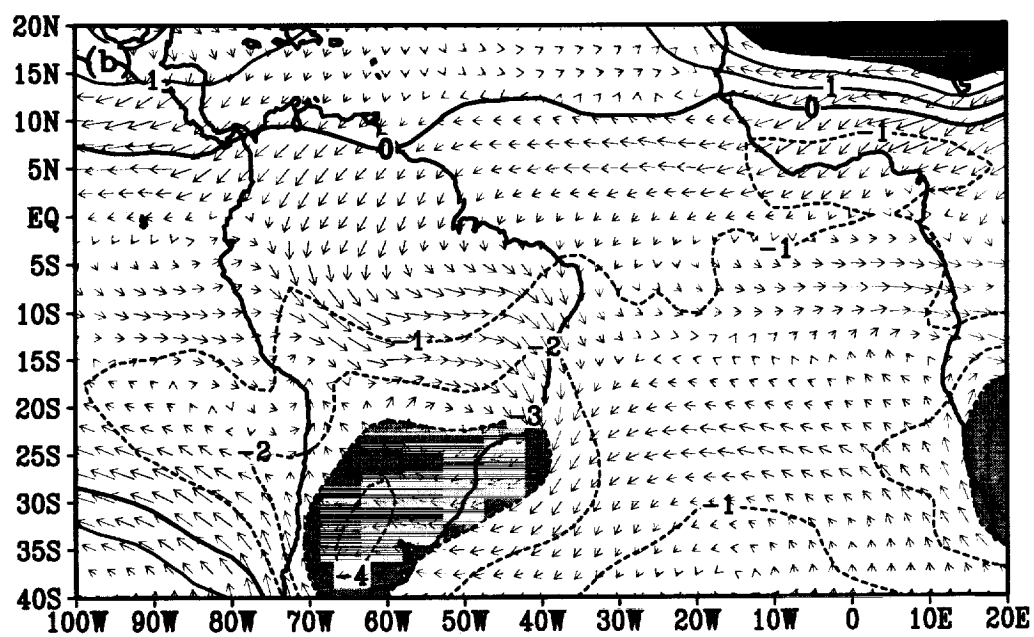
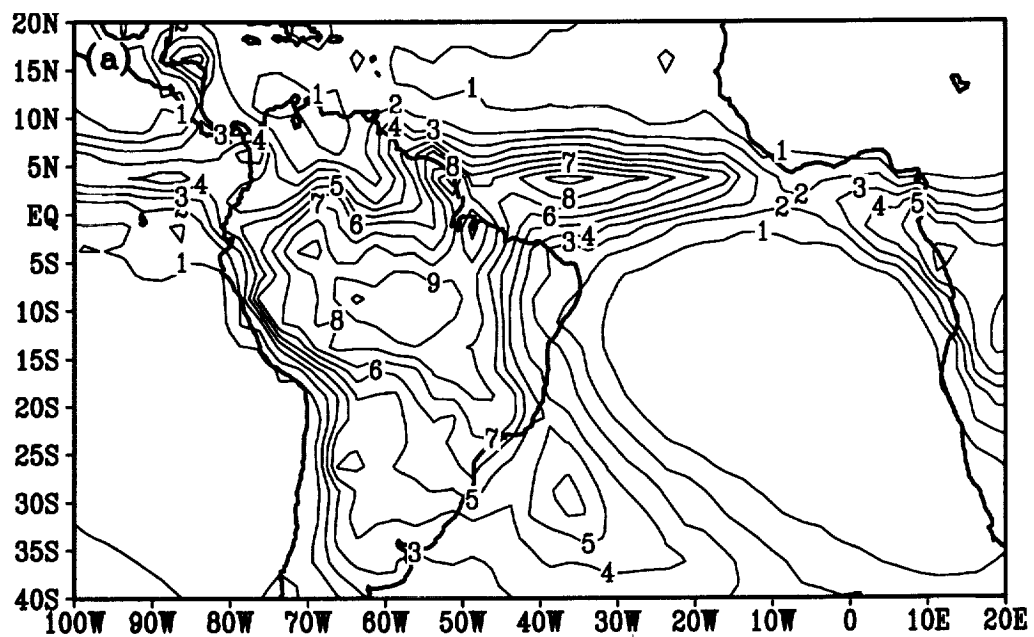
Figure 6 Vertical cross-section of DJF temperature (K) along 15°S, showing the climatology of the departure from the zonal mean (top panel), the 1997/98 anomaly (middle panel) and the 1998/99 anomaly (bottom panel).

Figure 7 Vertical cross-section of DJF zonal wind zonally averaged from 80°W to 50°W (m/s), showing the climatology (top panel), the 1997/98 anomaly (middle panel) and the 1998/99 anomaly(bottom panel).

Figure 8 Same as Fig.7 except for DJF meridional wind along 15°S (m/s).

Figure 9 Time evolution of key components (as labeled in each subpanel) of the SASM during 1997-99. The cross sign denotes the climatological annual cycle and the circle the actual observations during 1997-99.

Figure 10 Schematic illustration of the responses of the SASM climate system to El Niño, showing the relationship of rainfall anomalies to key circulation features: the low level jet (LLJ), the Bolivia High (BH), the South Pacific High (SPH), the South Atlantic High (SAH), the anomalous Walker Circulation, the induced local Hadley Circulation, and the subtropical westerly jetstream.



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Fig. 1

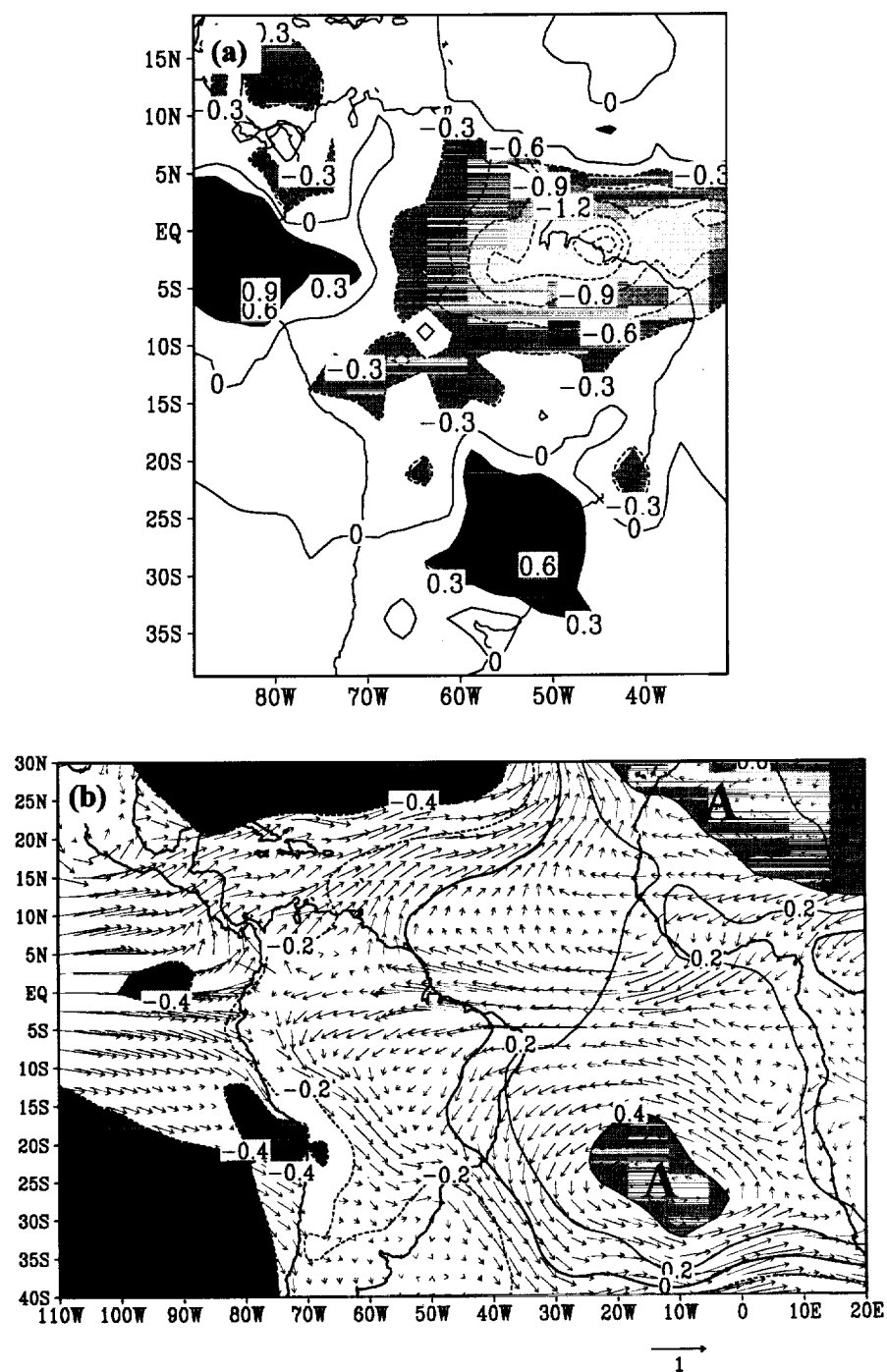


Fig. 2

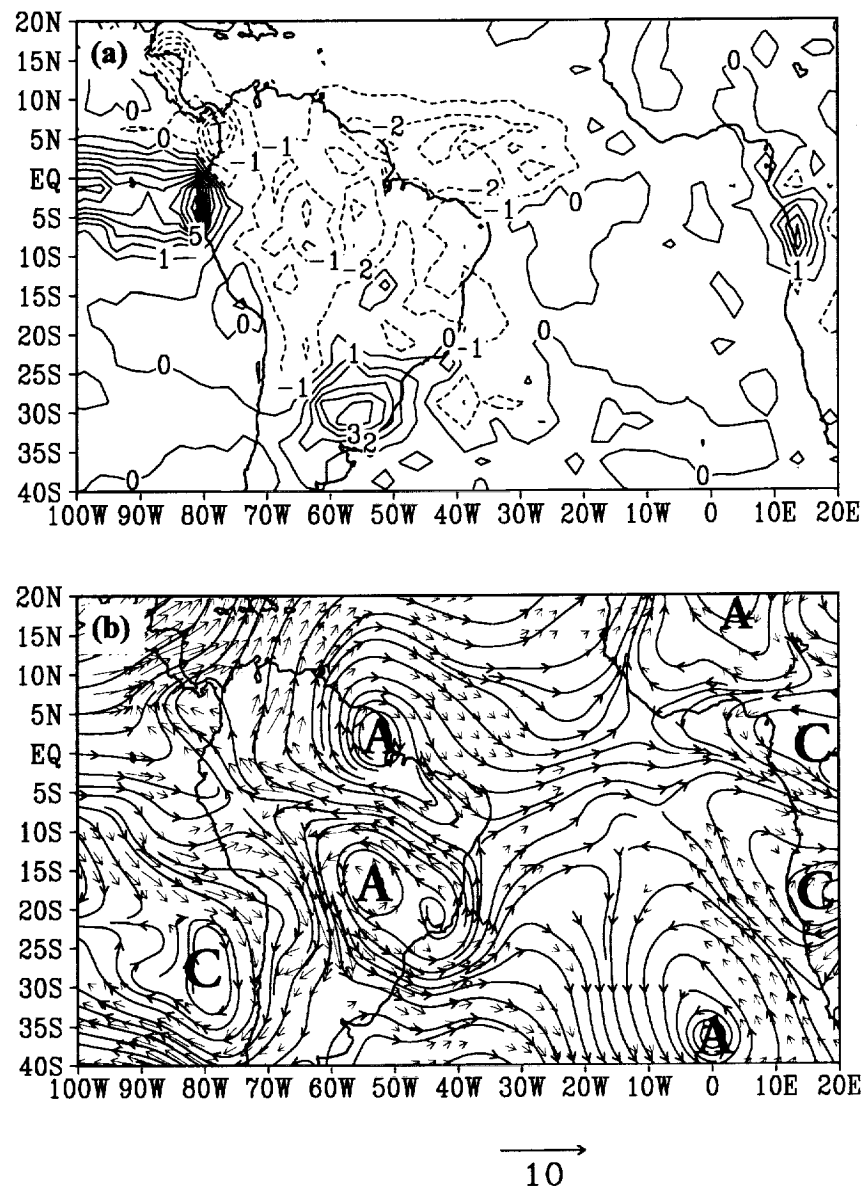


Fig. 3

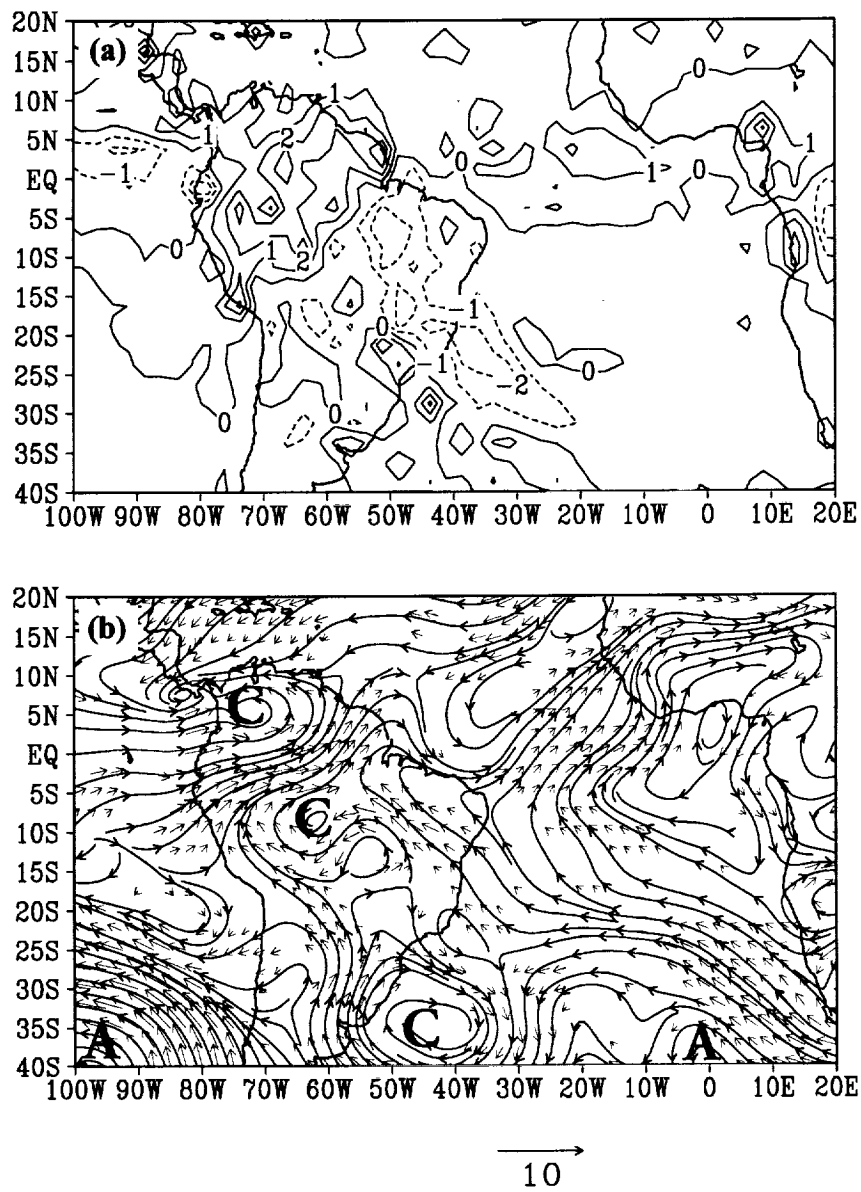
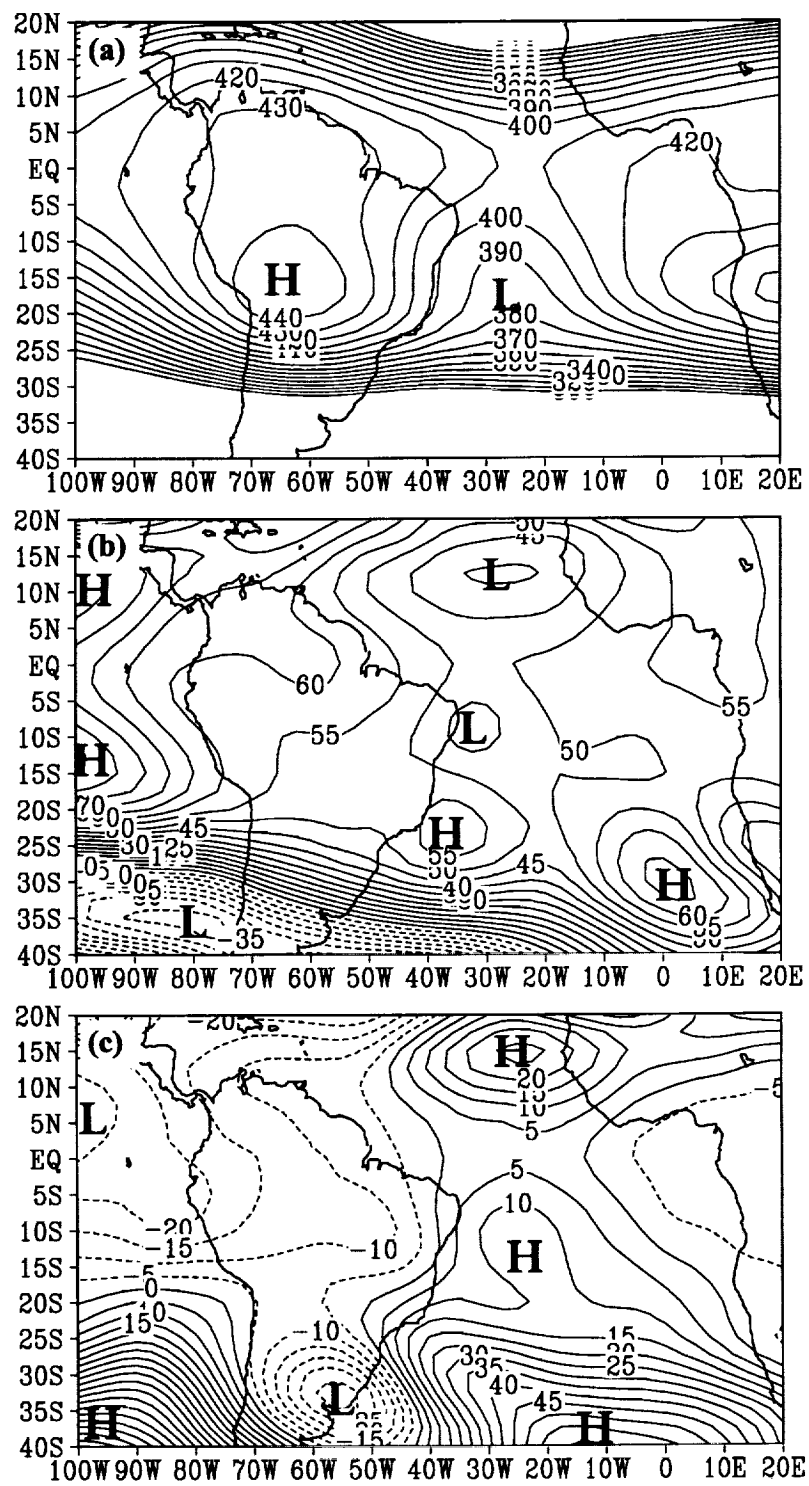
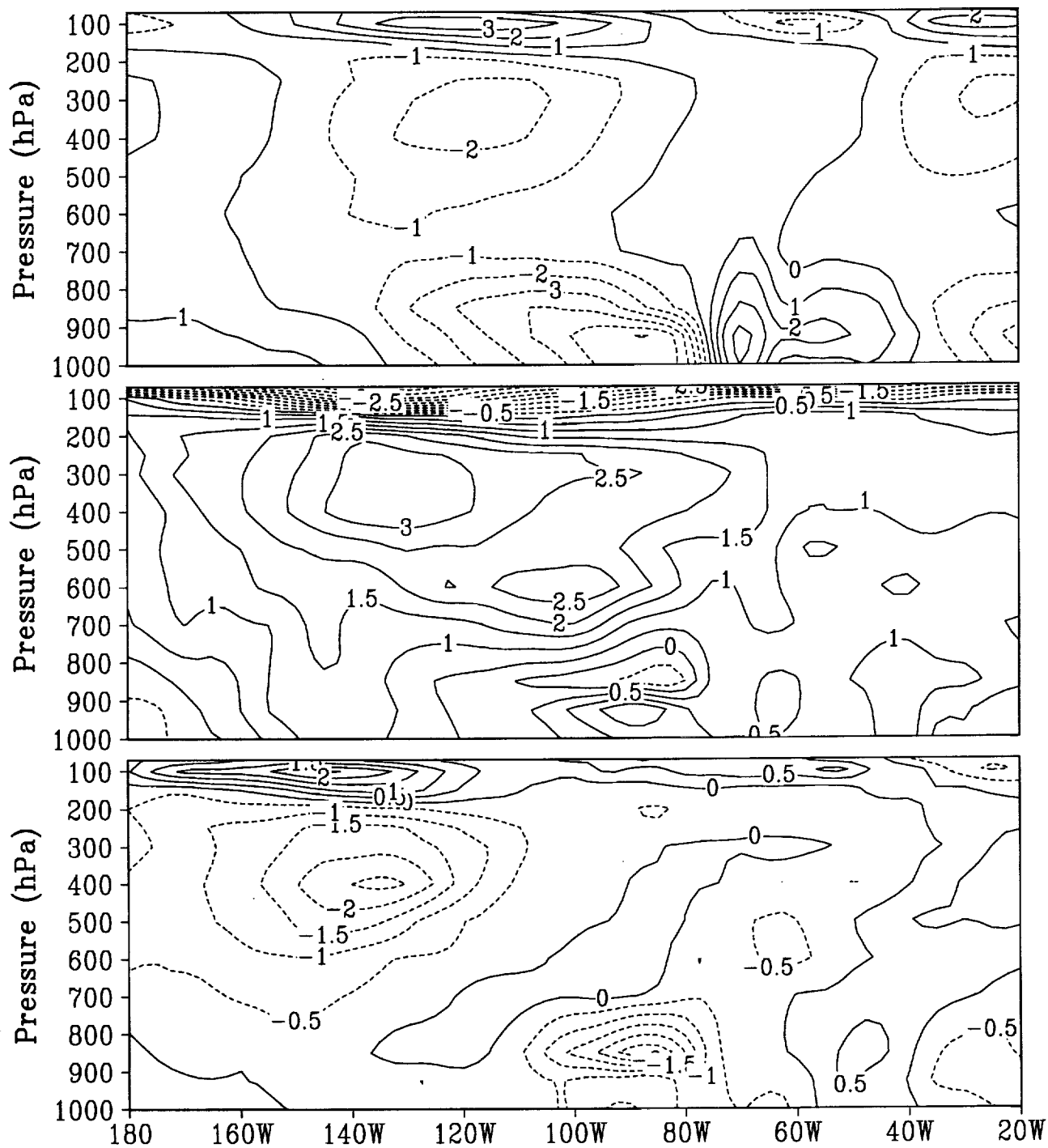


Fig. 4



**Fig. 5**



**Fig. 6**

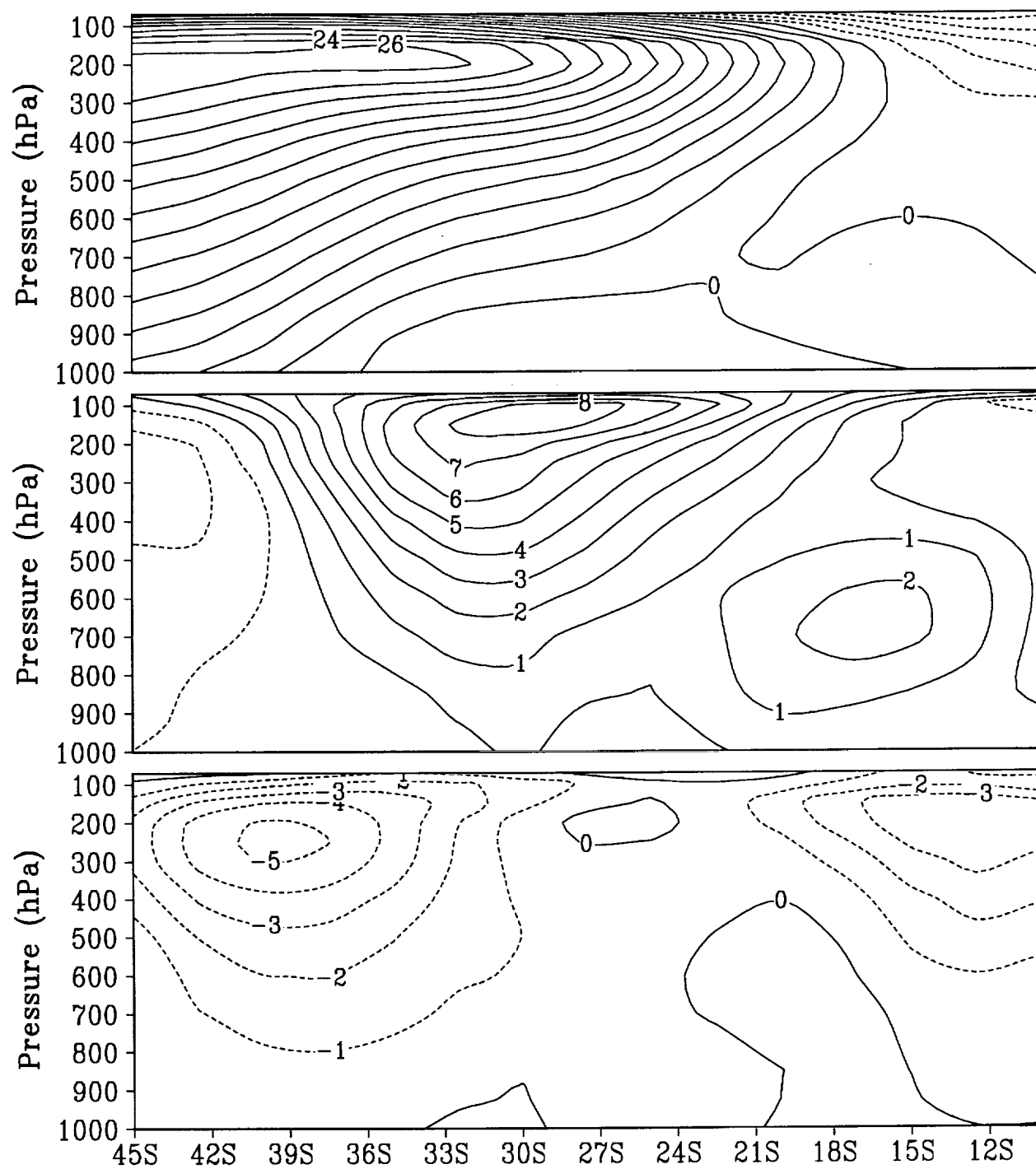


Fig. 7

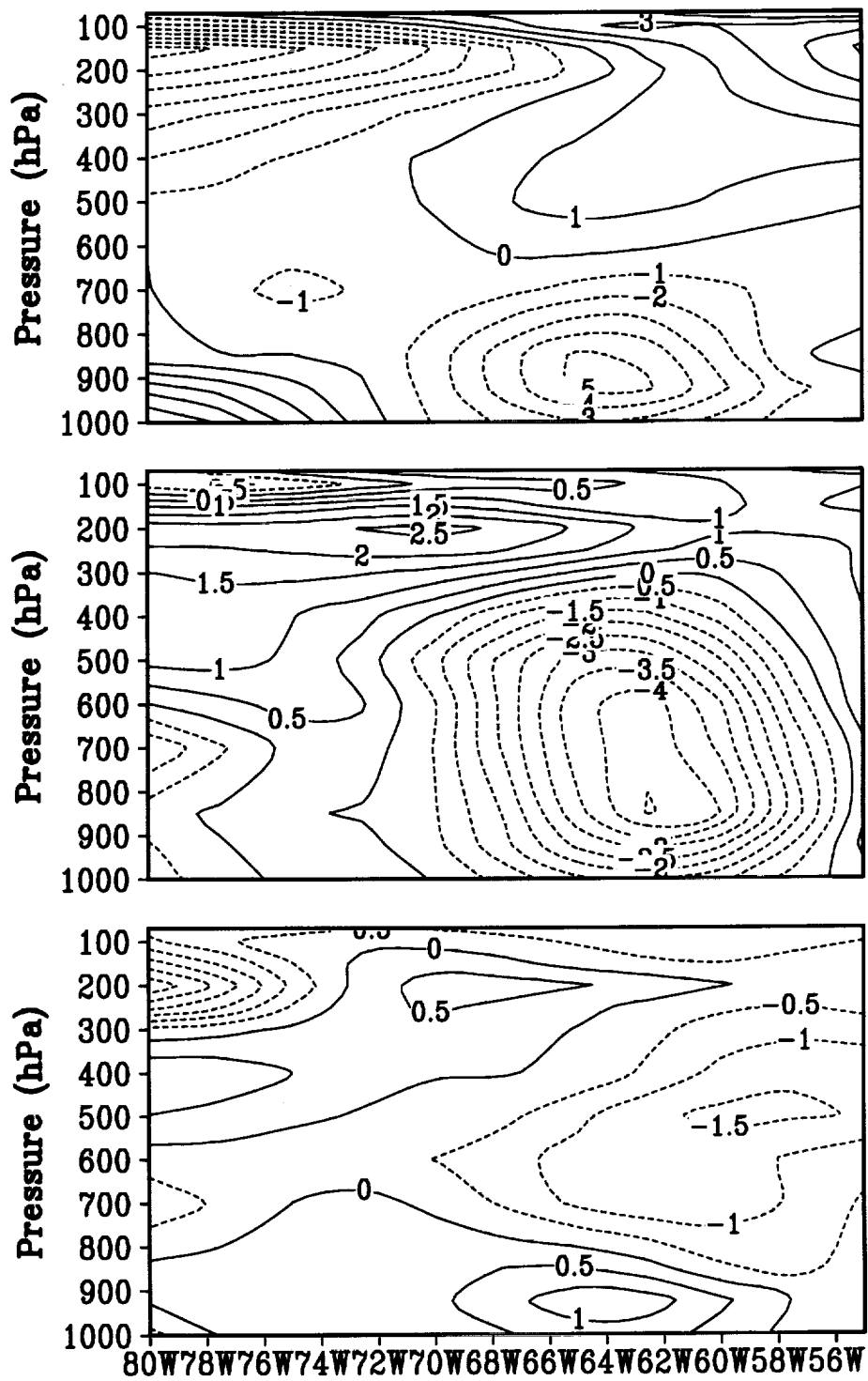


Fig. 8

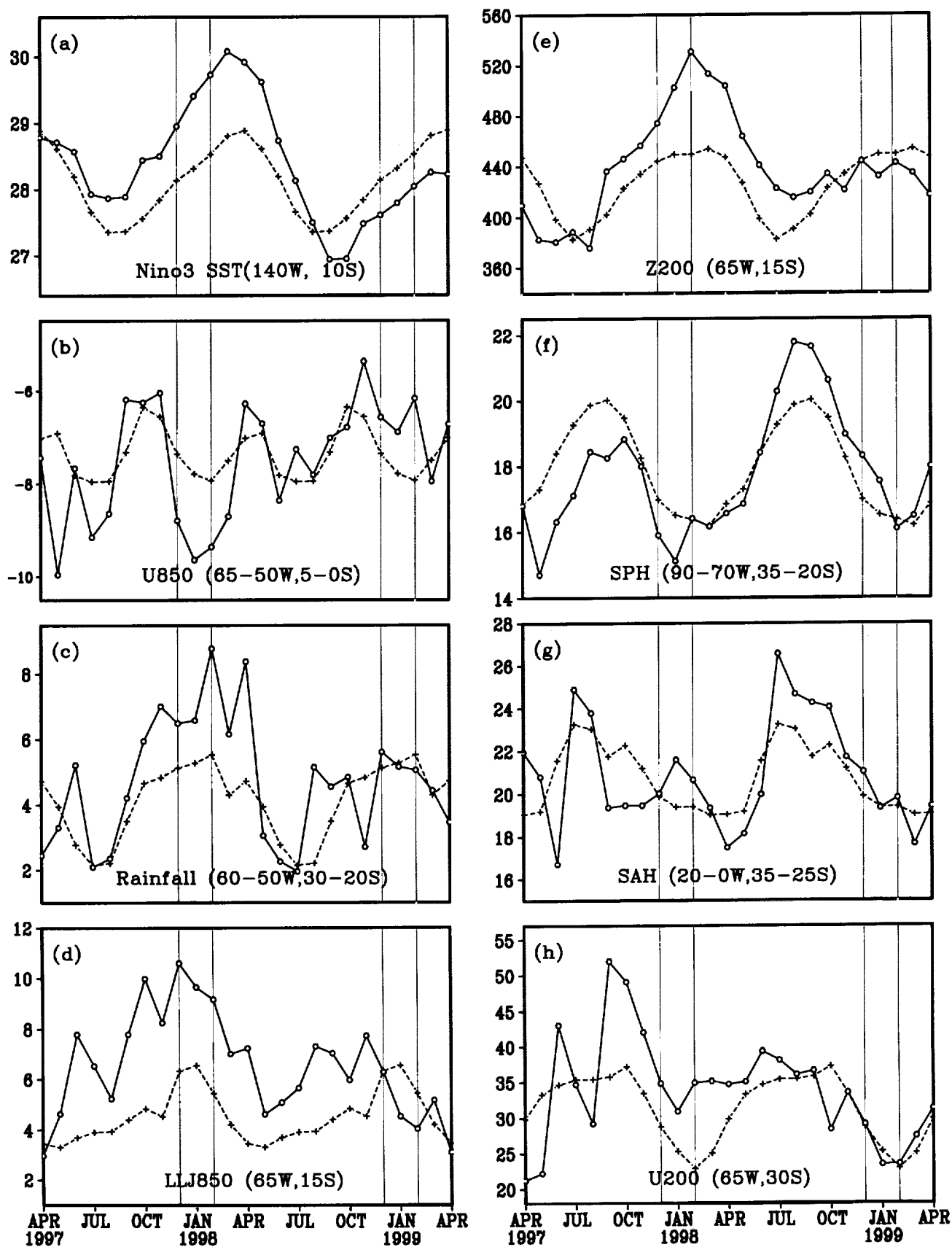


Fig. 9

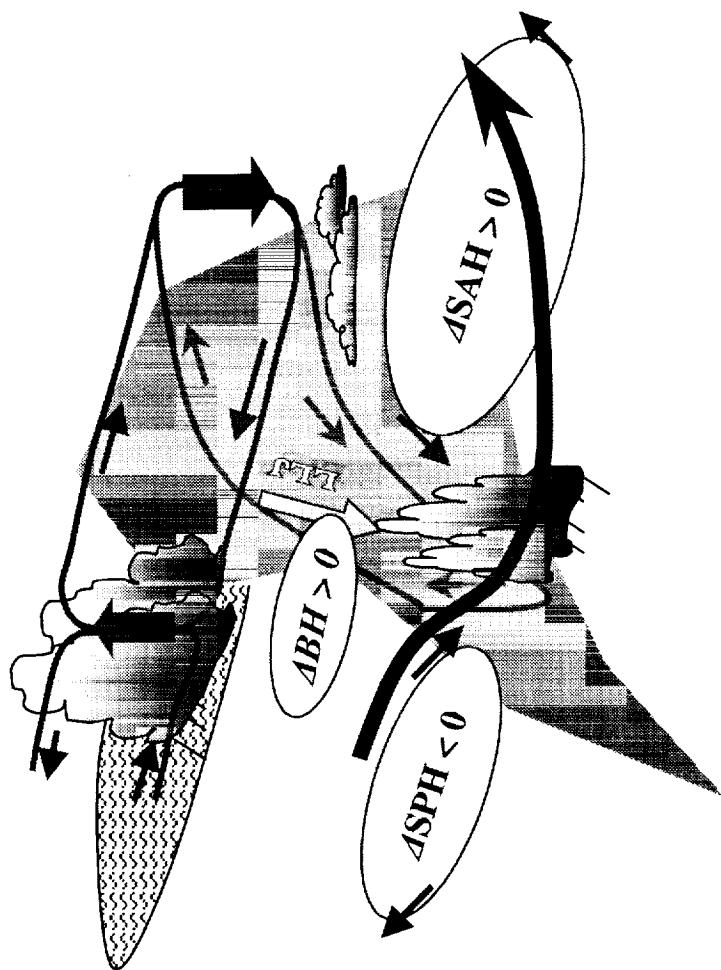


Fig. 10